INTRODUCTION

The Sierra Nevada Global Change Research Program began in 1991 as a peer-reviewed, competitively-funded component of the National Park Service's (now USGS-BRD's) Global Change Research Program (Stephenson and Parsons 1993). While Sequoia, Kings Canyon and Yosemite national parks form the core study areas, the full study region encompasses adjacent federal and state lands, and stretches from north of Yosemite to the southern end of the range, from the San Joaquin Valley in the west to the Owens Valley in the east (Fig. 1).

The goal of the Sierra Nevada Global Change Research Program is to understand and predict the effects of global changes on montane forests. Forests provide humanity with economically important and often irreplaceable ecosystem products and services, such as watersheds, wood, fiber, biodiversity, and recreational opportunities. Ongoing global changes have potentially far-reaching effects on these products and services, and hence on society. Land-use change (an increasingly important form of global change) already has affected the health and resilience of many forests, leading to controversy on how best to counteract the changes (e.g., Stephenson 1999). Additionally, forests sequester the majority of the terrestrial biosphere's carbon (Kirschbaum et al. 1996), making them key components of the global carbon cycle and key contributors of biogenic feedbacks to global climatic change (Melillo et al. 1996). For these and other reasons, the Intergovernmental Panel on Climatic Change has identified a mechanistic understanding of forest responses to climatic change as a high priority for research.
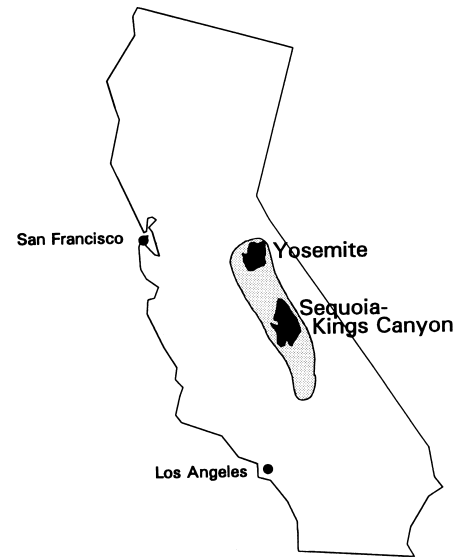

Figure 1. Locations of study areas within California.

CONCEPTUAL APPROACH

By far the greatest limitation to understanding and predicting the effects of future global changes is the lack of a precise mechanistic understanding of how contemporary forest structure and function are controlled by the physical environment, disturbances, and biotic processes. Our research program therefore places landscape patterns within the context of the physical template (abiotic factors such as climate and soils), disturbances (such as fire), and biotic processes (demography, dispersal, growth, and competition) (Fig. 2). Our program focusses on developing a mechanistic understanding of this simple model as it applies to Sierra Nevada forests in particular, but also for the montane forests of western North America in general.

The task of gaining a mechanistic understanding of forest dynamics is beset with notoriously severe problems. Most of these problems result from the great spatial and

temporal scales encompassed by forest dynamics, which often preclude many forms of experimental manipulation. As a consequence, most researchers attempting to predict the consequences of global changes on forests have relied on computer models. However, predictions from computer models are only as good as the assumptions that drive them, and these are often untested and unrealistic (e.g., Loehle and LeBlanc 1996).

Figure 2. Agents of pattern formation

We have sought to overcome these problems through integrated studies organized around three themes: paleoecology, contemporary ecology, and modeling. All three consider the role of the physical template and disturbance in controlling biotic processes and responses.
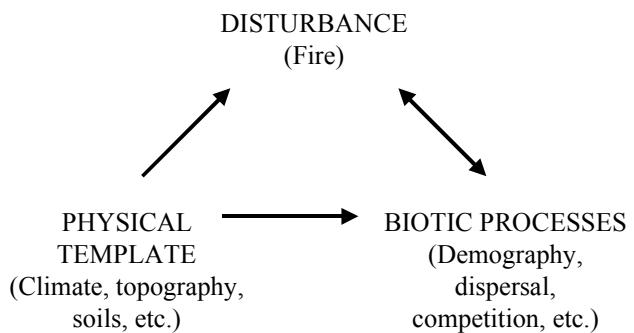
Paleoecological theme

The paleoecological theme focusses on understanding past climatic changes and the consequent responses of fire regimes and forests. The Sierra Nevada is endowed with an extraordinarily rich record of such changes. The region is unique worldwide in having at least four tree species from which multi-millennial tree-ring chronologies of climatic change can be derived (e.g., Hughes and Brown 1992, Graumlich 1993, Hughes and Graumlich 1996, Garfin 1998). Fire scars within giant sequoia tree-rings contain annual- and seasonal-resolution fire histories spanning the last several millennia, revealing a strong link between changing climate and fire regimes (Swetnam 1993). Additionally, charcoal trapped in meadow sediment documents changes in fire regimes spanning the entire Holocene (Anderson and Smith 1997). Biotic response to changing climate and fire regimes are recorded in the age structures of existing forests and in the woody remnants of past forests (Stephenson 1994, Lloyd and Graumlich 1997), and in Holocene-length records of pollen trapped in meadow sediments (Anderson and Smith 1994).

Contemporary ecology theme

The contemporary ecology theme takes advantage of the Sierra Nevada's substantive climatic gradients as "natural experiments," allowing us to evaluate climatic mechanisms controlling forest composition, structure, and dynamics (e.g., Halpin 1995, Kern 1996, Stephenson 1998, Stephenson et al. 1998 and *in prep.*). A fortuitous combination of extreme environmental gradients and physiographic complexity makes the Sierra Nevada mountain range an ideal laboratory for such an approach. Elevation rises from near sea level to 4,418 m in less than 100 km horizontal distance -- one of the most extreme elevational gradients in temperate North America. A steep temperature gradient -- from warm mediterranean to cold alpine -- parallels the elevational gradient, and in turn, is overlain by a gradient of decreasing precipitation from west to east. These climatic gradients combine with highly variable soils and topography to create a physical

template that includes an extraordinary range of local site water balances (Stephenson 1998).

Modeling theme
        The modeling theme integrates findings from the paleoecological and contemporary studies, which, of necessity, are conducted at local spatial scales. Modeling is the indispensable vehicle for scaling up our mechanistic findings to regional landscapes, and is the key to predicting which parts of montane landscapes may be most sensitive to future environmental changes (e.g., Urban 2000).

        Importantly, our research program seeks to generalize its findings beyond the Sierra Nevada. To this end, we are collaborating with several ongoing research efforts elsewhere in western North America. Much of our external collaboration is with three other global change research programs within the USGS-BRD's Western Mountain Initiative: Olympic, Glacier, and Colorado Rockies (see the Western Mountain Initiative web site at *http://www.nrel.colostate.edu/brd_global_change/theme_mountain.html*). Other collaborations are listed later in this document.
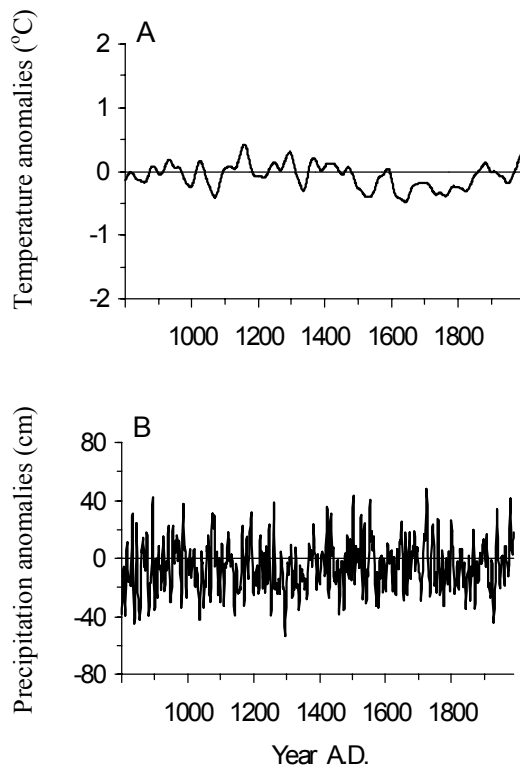
RESULTS OF PREVIOUS WORK

The Sierra Nevada Global Change Research Program has leveraged its funds by collaborating with more than 20 scientists from 10 universities and research organizations, contributing to more than 160 publications and abstracts since 1991, including six M.S. and seven Ph.D. theses (see our web page and full bibliography at *http://www.werc.usgs.gov/sngc/*).

        Integration of our past work is facilitated by considering results within the context of the physical template, disturbance, and biotic processes (Fig. 2), and evaluating their contributions to our understanding at scales from forest stands to landscapes and regions. Hughes and Graumlich's (1996) 8000-year climatic reconstruction for the Sierra Nevada reveals that the warmth of the 20th Century has been experienced most recently during the 12th and 14th centuries AD (Graumlich 1993) (Fig. 3). A sobering feature of these records is the documentation of regular multi-decadal droughts, of much greater length and severity than any experienced in the last 100 years. At a

Figure 3. Tree ring reconstructions of (A) past temperature and (B) precipitation in the Sierra Nevada. From Graumlich (1993).

regional scale, these droughts are predictable from subcontinental-scale atmospheric anomalies over the Pacific and Western North America, and can be tied to tree growth anomalies (Garfin 1998).

Our paleoecological records also provide insights into climatic, anthropogenic, and topographic controls of disturbance regimes, particularly fire. A sharp peak in charcoal deposition in montane Sierra Nevada meadows is evident in the early Holocene (ca. 9000 years ago), followed by millennia of low charcoal deposition (Anderson and Smith 1997). Charcoal deposition has increased again for about the last 4500 years. The latter increase corresponds to changes in forest composition (Anderson and Smith 1994). Sierra Nevada forests also have produced one of the longest and best-replicated networks of tree-ring based fire-history reconstructions in the world (Swetnam et al. 1992, Swetnam 1993, Caprio and Swetnam 1995, Swetnam et al. in prep.). Swetnam's >2000 year annual- and seasonal-resolution fire-scar chronologies from sequoia groves demonstrate substantial variation in fire frequency and size across all temporal and spatial scales (Fig. 4). Before about 1850, predominantly low- to moderate-intensity surface fires burned within portions of any given sequoia grove, on average, about every 3 to 8 years, but of particular note is the occurrence of occasional high-intensity fires. With the demise of Native Americans, introduction of livestock grazing, and suppression of lightning fires following Euroamerican settlement, most grove areas have experienced a 100- to 130-year period without fire -
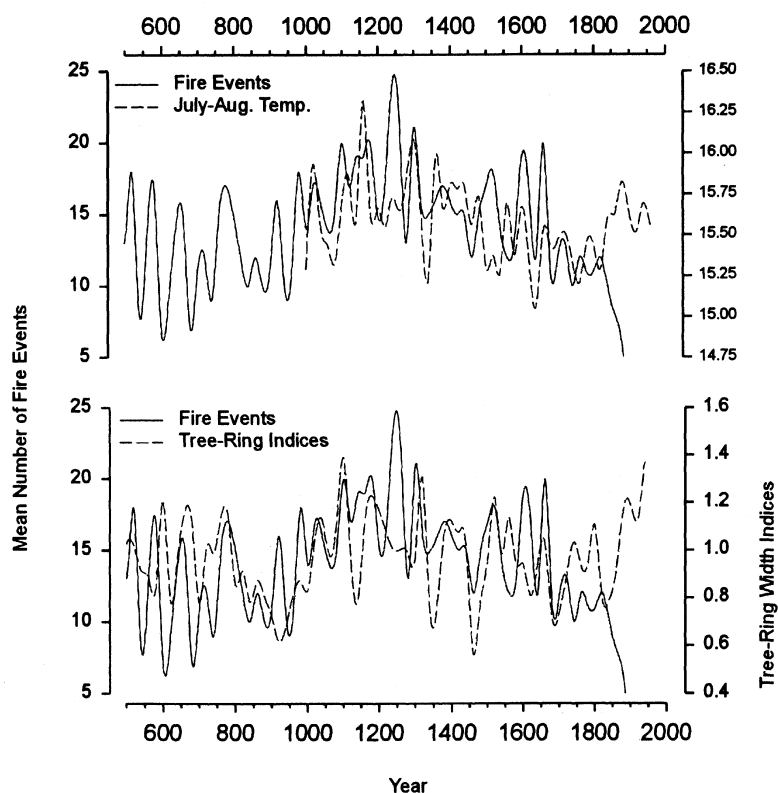

Figure 4. The past relationship between temperature and fire frequencies in the Sierra Nevada as determined by dendrochronological records. From Swetnam 1993.

- a fire-free period that is unprecedented over at least the last several millennia. Fifty-five additional fire-scar chronologies have been developed along four elevational transects, greatly extending the elevational range of fire-scar chronologies. Fire frequencies along these transects are strongly and negatively correlated with elevation, demonstrating a strong link between climate and fire regimes (Swetnam et al. 1998). Fire chronologies from both sequoia groves and the elevational transects were highly synchronous across

temporal scales of years to decades. Moreover, these synchronous patterns were well-correlated with climatic changes inferred from the other tree-ring studies (see the preceding paragraph). Variations in giant sequoia fire regimes generally corresponded with century-scale climatic episodes (high fire frequencies during the Medieval Warm Period, and low fire frequencies during the Little Ice Age).
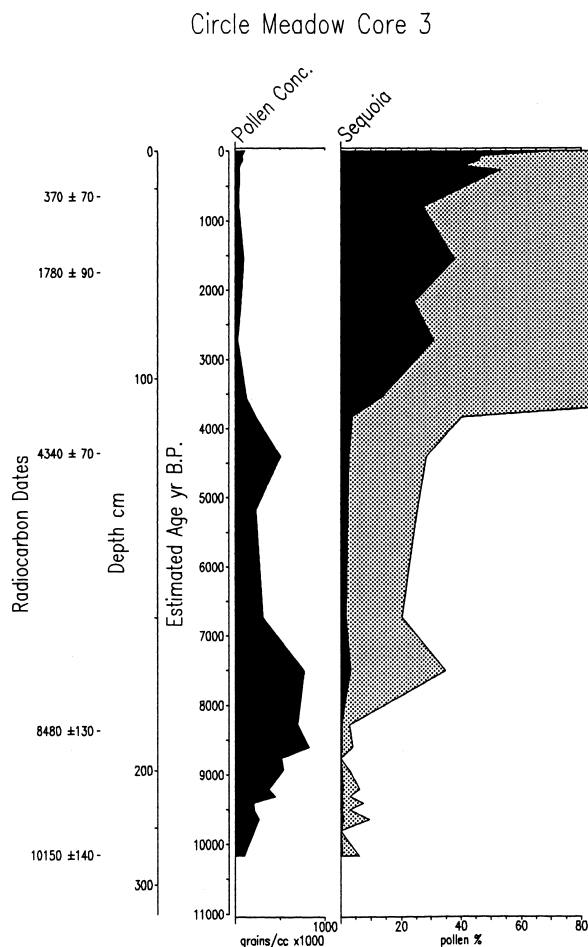
The strong linkage between climate, disturbance, and vegetation is illustrated in pollen records. Within present sequoia grove boundaries, sequoias (and firs) began to increase dramatically in importance relative to pines about 4500 years ago (Fig. 5), coincident with a slight global cooling and an increase in charcoal deposition (Anderson 1994, Anderson and Smith 1994, Anderson and Smith 1997). While we have clearly demonstrated that climate and fire regimes have varied -- sometimes substantially -- within sequoia groves during the last few millennia, the combined effect on giant sequoia populations in large groves, as demonstrated by age-structure studies, has been only moderate (Stephenson 1994 and in prep.). Land use change has had a greater effect on forests than several millennia of climatic and fire change; that is, the greatest anomaly in sequoia regeneration over at least the last two millennia has been a nearly complete regeneration failure attributable to modern fire exclusion (Stephenson 1994 and in prep.).

Figure 5. Pollen records of the past abundance of giant sequoia in the Giant Forest, Sequoia National Park. From Anderson and Smith 1994.

Treeline forests, in contrast to giant sequoia populations, have responded more strongly to climatic changes and, unlike treeline dynamics elsewhere in the world, Sierra Nevada treelines are controlled by both temperature and precipitation (Lloyd and Graumlich 1997 -- this work was given the Ecological Society of America's Cooper Award in 1998). Remnant wood up to 60 vertical meters above current treeline is testimony to the fact that 20th century climatic variability in the Sierra Nevada has yet to exceed the bounds of climatic variability over the past 3500 years.

Across scales from local Sierra Nevada forest stands to continents, water balance equations have been used successfully to explain vegetation distribution (Stephenson 1990, 1998) (Fig. 6). Factors that affect site water availability (e.g., soil depth) and evaporative demand (e.g., slope aspect) have intrinsically different effects on site water balances (Stephenson 1998). These differences are evident in forest patterns. Spatial hydrology (e.g., topographic convergence, lateral hydrologic fluxes) represents an
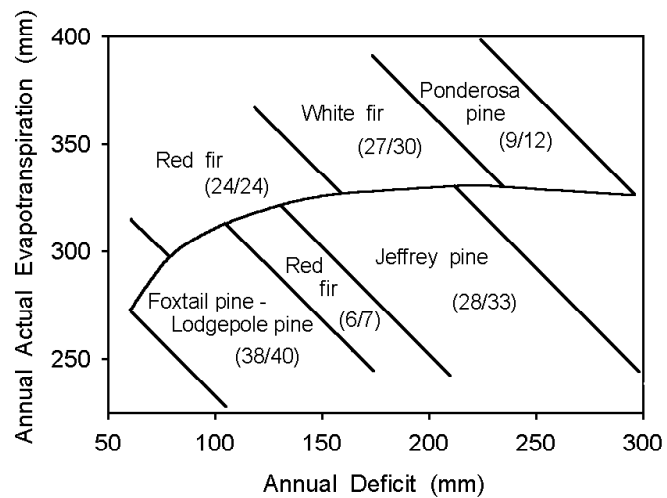

Figure 6. Forest types of the Sierra Nevada in relation to actual evapotranspiration and water deficit. From Stephenson 1998.
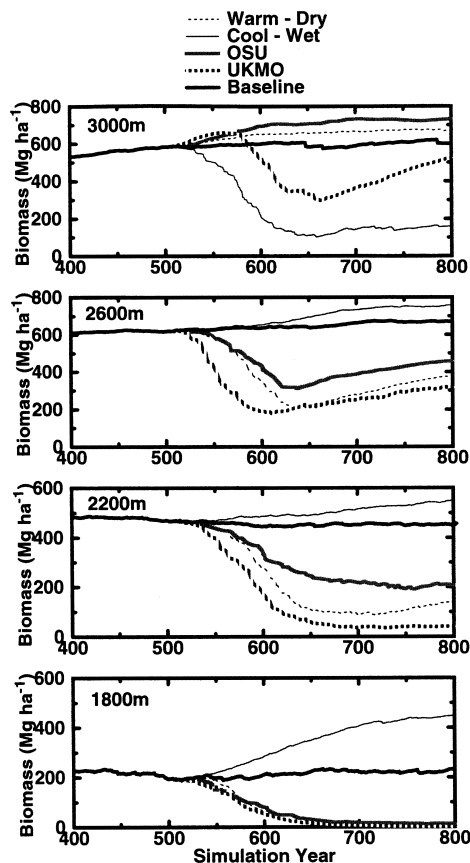

Figure 7. Total woody biomass simulated at four elevations for four climatic change scenarios and baseline conditions using ZELIG. From Miller and Urban 1999.

additional parameter with predictive power for explaining forest distribution (Halpin 1995). Tree death rates increase sharply with decreasing elevation (i.e., increasing temperature) (Stephenson et al. 1998, and in prep.). The increase in death rates is independent of stand structure and composition and is driven by a dramatic increase in death by biotic factors (insects and fungi) with decreasing elevation, thus indicating a potential linkage between climate (in this case temperature) and biotic interactions. Forest carbon turnover, both absolute and relative, increased with decreasing elevation (increasing temperature) (Stephenson et al. in prep.).

Modern fire regimes depend heavily upon rate of fuel accumulation and this is reflected in annual accumulation differences between ponderosa pine and white fir stands (van Wagtendonk et al. 1998a, 1998b). FARSITE, a user-friendly Windows-based fire area simulator, was initiated as part of the Sierra Nevada Global Change Research Program and is currently the most widely used tool for planning prescribed fires and predicting the behavior of wildfires (Finney 1995, 1998).

The Zelig gap model (version Facet) acts as an integrative framework for coupling physical template, disturbance, and biotic processes, and is validated with both historical and contemporary forest and climate reconstructions (Fig. 7). It can be successfully scaled up (MetaFor) to replicate actual distributions of Sierra Nevada tree species along elevational gradients (Urban et al. 1999 and in press). This model corroborates Stephenson (1998) by predicting fundamentally different effects of water availability and evaporative demand on site water balances (Urban et al. in press).

We have also emphasized the radically different natural scaling of factors affecting site water balances, e.g., precipitation and temperature that vary over hundreds of meters in elevation, while soil depth varies over centimeters (Urban et al. in press). Further, some of these factors (temperature, precipitation) vary considerably through time and might be expected to change under greenhouse scenarios; by contrast other important factors (soil texture, depth, and microtopography) vary principally over space and are less likely to change under greenhouse scenarios. This distinction is important for global change research as most previous work has focused largely on temperature and precipitation, whereas our work suggests that other factors (especially soils and microtopography) are at least as important to the water balance and ecosystem response.

Our goal in modeling fire has been to reproduce the statistics of the Sierra Nevada fire regime, based on actual mechanistic processes that couple climate, forests, and fire. This is in contrast to other modeling approaches that "feed" the model fire statistics (e.g., mean fire size, frequency) as input parameters. Based on first principles (such as modeled fuel accumulation, water content, and continuity), Zelig successfully reproduces the observed paleoecological record of fire frequencies across the elevational gradient (Miller 1998, Miller and Urban 1999a-c). Further analysis of the model reveals that lower-elevation fires are constrained by anomalous wet years (which accelerate fuel accumulation), while high-elevation fires are constrained by anomalous dry years (which are critical to lowering fuel moisture). These findings are supported by our paleoecological reconstructions of fire regimes (Swetnam et al. 1998). Thus, the fire regime is driven by both the mean and variance in climate, but the direction of this variation itself changes with elevation.

We have placed strong emphasis on communicating the management implications and applications of our work. For example, Graumlich found that the last 50 years in California have been among the wettest of the last millennium, and that multi-decadal droughts of much greater length and severity than any experienced in California during the last century have occurred regularly in the past. These findings served as an abrupt wake-up call for California water resource planners, and received national attention. Swetnam's fire reconstructions are now used by land managers up and down the Sierra Nevada as a target for restoring pre-Euroamerican fire regimes. Stephenson's investigation of the effects of fire regimes on forest pattern and dynamics have led to modifications in both prescribed fire and timber harvesting approaches in the Sierra Nevada. Van Wagtendonk has provided an important tool to resource managers by the demonstrated use of basal area and live crown ratio to predict annual fuel increments for most Sierra Nevada trees. Finney's FARSITE fire behavior and spread model, initiated as part of our program, has become the most widely-used fire model by North American land managers. Miller and Urban have provided land managers with projections of the consequences of natural fire, prescribed fire, and timber harvest on Sierra Nevada forests.

Urban's Zelig model also has proved to be an important tool for evaluating the impact of "unnatural" fuel accumulation on fire intensity and thus on stand structure.